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Assessment of pulse height defect in passivated implanted planar Si detectors used for channeling measurements with slow, highly charged heavy projectiles

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Abstract

The pulse height defect (PHD) of slow, highly charged ^{12}C, ^{16}O, ^{40}Ar and ^{84}Kr ions in a passivated implanted silicon detector has been measured. The detector is part of the channeling setup at the Frankfurt ECR/RFQ installation for beams of highly charged ions. In this experiment the modification of the charge states under channeling conditions in thin silicon membranes is measured. The charge states of the scattered ions are separated by post-acceleration. The PHD is an important input for the energy calibration. It allows the analysis via a parametrization which relates it to the true energy and the order number of the ions through a simple power law. © 2002 Published by Elsevier Science B.V.

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1. Introduction

This work is a continuation of the cooperation between the groups of the IKF, Frankfurt and the ATOMKI, Debrecen in channeling experiments with slow, heavy and highly charged ions on thin monocrystalline metal membranes [1]. The experiments were performed on the Frankfurt ECR-RFQ accelerator and its attached channeling and post-acceleration setup. A detailed description of this setup is given in an earlier paper [1]. The energy and charge state analysis of the transmitted ions under random and channeling conditions demands for an exact knowledge of the energy calibration and detection efficiency of the semiconductor detector used. For this reason the pulse height defect (PHD) of the passivated implanted planar silicon detector was measured. The PHD is the difference in detected energy between heavy ions and light ions (e.g. protons, α-particles) of the same kinetic energy.

By energy transfer from the ions to the electronic system of the semiconductor electron–hole pairs are generated, which define the energy of the impinging ions. The difference (PHD) between the true energy and the detected energy in an α-calibrated detector stems from three effects: (1) The

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window defect E_w, that is the energy loss of the heavy ions in the dead layer of the detector. (2) The nuclear energy loss E_n of the non-ionizing collisions of the slow, heavy ions with the atoms of the detector. (3) The electronic "rest defect", that is a recombination of electron–hole pairs, a charge capture or a charge diffusion within the detector, which all lead to incomplete charge accumulation of electron–hole pairs and a reduction of detected pulse height [2]. Counteracting this reduction (PHD), an increase of the pulse height is observed [3,4], which depends on the stopping power of the ion in Si. This effect is assumed to result from a decrease of the electron–hole generation energy ϵ with increasing (de/dx) [3].

2. Results and discussion

The PIPS detector is calibrated with a "3-line" α-source (^{239}Pu, ^{241}Am, ^{244}Cm) and a ^{148}Gd α-source ($E_\alpha = 3.183$ MeV). The energy calibration of the post-accelerator and the determination of the thickness of the Si membrane also is done by means of the α-sources. Fig. 1 shows the energy spectrum of the α-ions from the Am source. These ions should have a charge state of 2. By activating the post-accelerator with a voltage of −60 kV, the spectrum shifts by +120 keV, which confirms the charge state of the α-ions ($q_m = 2$) and shows the correctness of the acceleration voltage. The energy spectrum shifted by the Si membrane (oriented in random direction) is also shown. The thickness of the foil amounts to 1.46 ± 0.015 μm [5].

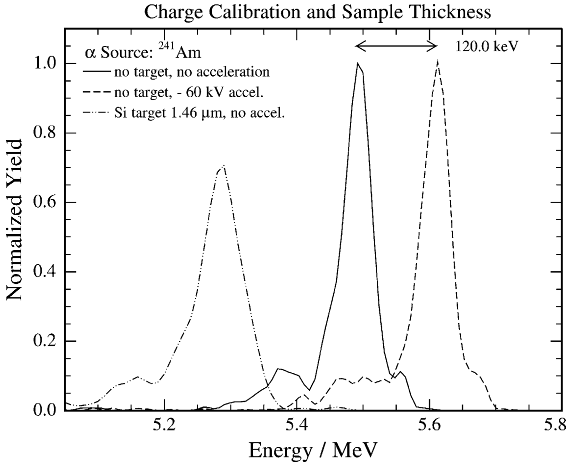

Fig. 1. Calibration of post-acceleration stage by ^{241}Am α-source. For a post-acceleration voltage of −60 kV the dashed spectrum is shifted by 120.0 ± 0.4 keV against the original spectrum; the charge state is 2.00 ± 0.01. The thickness of the Si membrane obtained from the energy loss of the α beam amounts to 1.46 ± 0.015 μm.

By using different gases at the same time, the ECR generates ions of different charge states for each of these gases. If, for example, a (mass m)/(charge q) relation of 4 is selected by the analyzer, the RFQ accelerator can be tuned to accelerate all ions with $m/q = 4 \pm 0.5$. Fig. 2 shows such spectra of $^{40}Ar^{+10}$, $^{16}O^{+4}$, $^{12}C^{+3}$ and $^{4}He^{+1}$, which have the same $m/q = 4$ and an energy, which amounts to the (RFQ energy/unit mass) times the mass of the accelerated ion ($E_{RFQ} = (E_{RFQ}/u) \times m_{ion}$). For $^{40}Ar^{+10}$ an energy of 6.96 MeV is measured by the analysing magnet after the RFQ. By applying a post-acceleration voltage of −60 kV the dashed spectra of Fig. 2 are observed. This energy gain ΔE divided by the post-acceleration voltage gives the observed mean charge state q_m, which amounts to 8.65 in case of $^{40}Ar^{+10}$. For $^{16}O^{+4}$ the energy gain is $\Delta E = 233$ keV and a $q_m = 3.9$ results, for $^{12}C^{+3}$ the data are $\Delta E = 175$ keV and $q_m = 2.9$ (Fig. 3). For

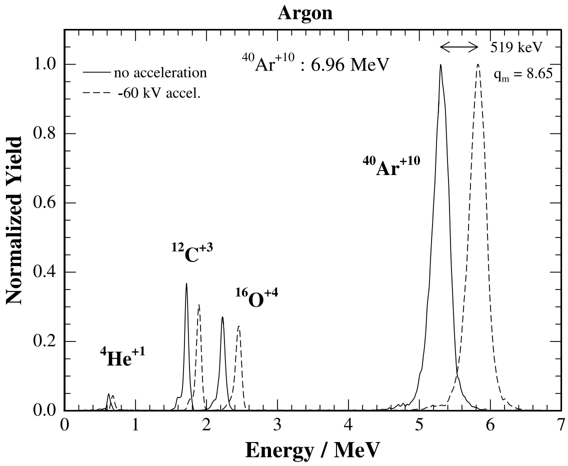

Fig. 2. Spectra of $^{40}Ar^{+10}$, $^{16}O^{+4}$, $^{12}C^{+3}$ and $^{4}He^{+1}$ with equal m/q taken without and with −60 kV post-acceleration.

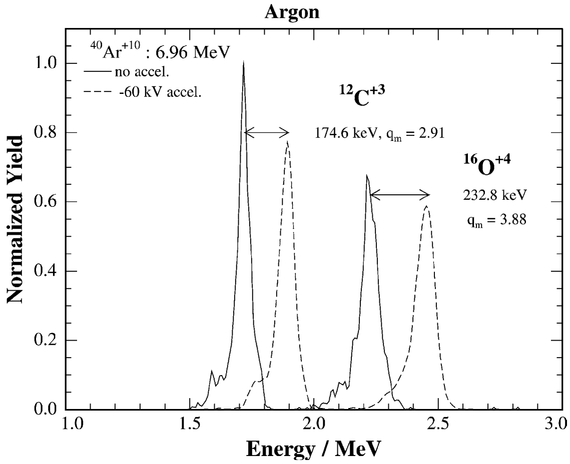

Fig. 3. Spectra of $^{12}C^{+3}$ and $^{16}O^{+4}$ without and with −60 kV post-acceleration. The PHD is reflected in the calculated charge states of 2.91 and 3.88 respectively, which are too small for the ions.

$m/q = 3.82$ the ions $^{84}Kr^{+22}$ and $^{40}Ar^{+10}$ (and traces of $^{82}Kr^{+21}$), are accelerated by the RFQ, the post-accelerated spectra and the energy shift ΔE respective mean charge state q_m are also displayed in Fig. 4.

These results show a remarkable PHD between the measured energy E_α and the RFQ energy (the true energy) E_{RFQ}. Moulton et al. [6] gave a simple power law for the parametrization of the PHD: $E_{PHD} = E_d - E_\alpha = 10^b E_d^a$, where a and b depend only on the order number Z of the ion: $a = a_0 + a_1 Z^2$; $b = b_0 + b_1/Z$. In this formula E_d is the deposited energy, that is $E_{RFQ} - E_w$, since only this part of the true energy is deposited in the active layer of the detector and may be converted into measurable pulse height. The dead layer thickness T and therefore the energy loss E_w for each ion in the PIPS is either known from the data sheet or can be measured be tilting the detector (this detector: $T \approx 50 \pm 5$ nm).

Fig. 5 shows a fit of the measured PHD for C, O, Ar and Kr ions to the above mentioned formula. It should be pointed out that only the spectra of the non-accelerated ions are included in the fitting procedure (the open symbols in Fig. 5). The results from the spectra of the post-accelerated ions and also some data from spectra of ions passing through the Si membrane in random direction (closed symbols) compare very well with the fitted curves. In Figs. 6 and 7 the energy spectra of $^{40}Ar^{+10}$ and $^{84}Kr^{+22}$ are corrected by the PHD formula. For Ar ions an energy shift of 630 ± 25 keV ($q_m = 10.5 \pm 0.4$) is obtained by

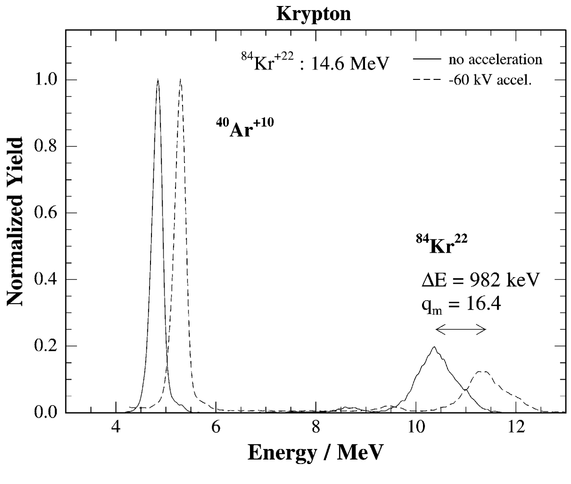

Fig. 4. Spectra of $^{40}Ar^{+10}$ and $^{84}Kr^{+22}$ without and with −60 kV post-acceleration. For Kr, a remarkable PHD of 338 keV (= {60 × 22–982} keV) is observed.

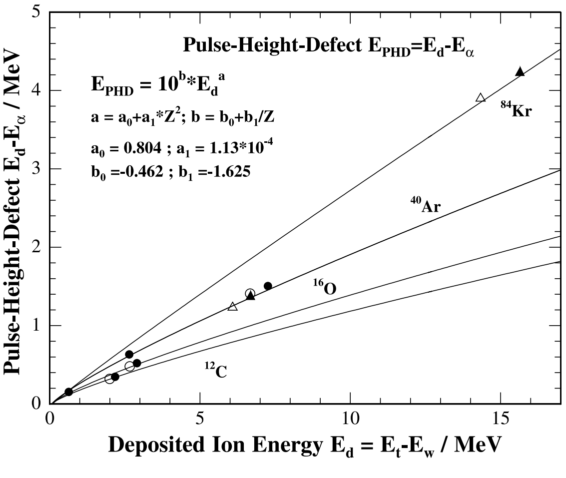

Fig. 5. Measured PHD of the PIPS detector for ions with different Z fitted to the formula $E_{PHD} = 10^b(E_{RFQ} - E_w)^a$, where $a = a_0 + a_1 Z^2$, $b = b_0 + b_1/Z$. Only the open symbols (no post-acceleration) were fitted. Closed symbols are from measurements with post-acceleration and from some spectra of ions passing through the Si membrane in random direction.

post-acceleration, for Kr ions the energy shift amounts to 1308 ± 30 keV ($q_m = 21.8 \pm 0.5$).

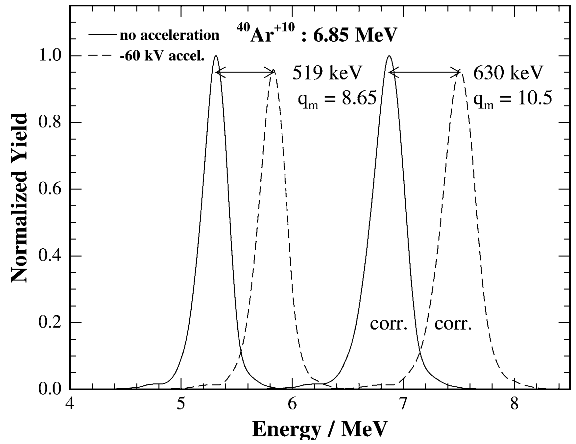

Fig. 6. Correction of the PHD for $^{40}Ar^{+10}$. The corrected energy shift amounts to 630 ± 25 keV resulting in a charge state of 10.5 ± 0.4.

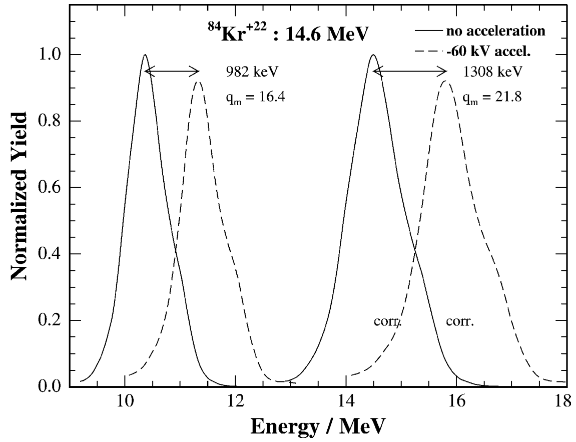

Fig. 7. Correction of the PHD for $^{84}Kr^{+22}$. The corrected energy shift of 1308 ± 30 keV gives a charge of 21.8 ± 0.5.

3. Conclusion

Since the general pulse height behavior of the PIPS detector is parametrized by the above mentioned fit, also spectra of ions transmitted through monocrystalline Si membranes can be corrected for the PHD. This is escpecially useful for ions in transmission channeling measurements, since their energy loss, which is the main goal of these investigations, cannot simply be calculated from the thickness of the sample [1]. The charge state distribution of the channeled ions can now also be calculated from the energy difference between the spectra of the non-accelerated and post-accelerated ions.

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